In Search of the Green Paradox: Announcement Effects of Title IV of the 1990 CAAA

Corrado Di Maria*
University of Birmingham

Ian Lange†
University of Stirling

Edwin van der Werf‡
Wageningen University

October 6, 2011

Preliminary: please do not quote.
Comments welcome.

Abstract

This paper presents the first empirical test of the green paradox. According to this paradox, well-intended policies may lead to detrimental environmental outcomes when imperfectly implemented. We use Title IV of the 1990 U.S. Clean Air Act Amendments as a case study. Our analytical model predicts that the time lag between the announcement of the cap on sulfur dioxide emissions and its implementation provided incentives to power plants to increase their energy input and to shift to high-sulfur coal, and hence to increase their emissions, during this period. We find strong evidence for the latter effect but no evidence for the former. These results have implications for currently contemplated climate policies.

JEL Classification: Q31, Q38, Q53, Q54, Q58.
Keywords: Green Paradox, implementation lags, announcement effects, climate policy, acid rain policy

1 Introduction

Environmental policies may lead to environmentally harmful effects if those policies deviate strongly from the first-best solution. They may be implemented too late, fail to cover all polluters, or adversely affect prices in another way such that perverse incentives are introduced and emissions or damages increase in the short run rather than decrease. This notion has been given new attention in recent times due to Sinn (2008). In his paper, Sinn argues that most climate policies currently implemented not only fail to provide a solution to the problem of increasing greenhouse gas emissions, but actually aggravate the problem by providing perverse incentives to the owners of stocks of fossil fuels, an outcome he called a 'green paradox'.

*University of Birmingham, Department of Economics, JG Smith Building, Edgbaston, Birmingham B15 2TT, United Kingdom, c.dimaria@bham.ac.uk. Di Maria is also a CESifo Research Network Associate.
†University of Stirling, Department of Economics, 3B72, Stirling FK9 4LA, United Kingdom, i.a.lange@stir.ac.uk.
‡Wageningen University, Environmental Economics and Natural Resources Group, Wageningen 6700 EW, The Netherlands, edwin.vanderwerf@wur.nl. Van der Werf is also a CESifo Research Network Fellow.

At the heart of the green paradox lies the change in supply behavior of resource owners in response to environmental policy: the policy changes the prospects of resource owners to sell their stocks over time, thus they change their supply pattern, which in turn affects the equilibrium resource rents. When policy makers fail to take into account the response of resource owners to the policy shock, this change in the path of resource demand – and hence emissions – may not be the change they intended. Since Sinn's thought-provoking paper, a large literature, based on analytical and simulation models, has developed. In their review of this literature, Van der Werf and Di Maria (2011) identify four imperfect policy approaches through which a green paradox may arise. First, the implementation lag that is usually present between the public announcement of a policy and its implementation (Title IV of the 1990 U.S. Clean Air Act Amendments, the Kyoto Protocol, the European Union Emission Trading Scheme) may result in an increase in emissions in the period between the announcement and the implementation (Di Maria, Smulders, and Van der Werf, 2008; Smulders, Tsur, and Zemel, 2010). Second, a "gradual greening" of policy, whereby the user price of the pollutant increases over time through a rising tax path, may make it profitable for owners of polluting resources to steepen their extraction path, which can result in an increase in early emissions and climate damages (Hoel, 2010, 2011a). Third, the policy may fail to cover all sectors or countries, and thereby induce an increase in emissions through "emissions leakage" (Eichner and Pethig, 2011; Hoel, 2011b). Finally, improvements in or subsidies for alternative energy technologies may induce resource owners to change their extraction path (Gerlagh, 2011; van der Ploeg and Withagen, 2010; Hoel, 2011b). Each of these policy approaches changes the expected time path of the rents for fossil resources, thereby changing the supply behavior of the owners and the equilibrium extraction and emission paths.

Thus far, the literature on the green paradox only used analytical or simulation models to study the effects of sub-optimal policies on emissions. We present an empirical analysis of the green paradox, based on the "policy implementation lag" mechanism. We use Title IV of the 1990 U.S. Clean Air Act Amendments (CAAA, Public Law 101-549) as a case study since it has strong similarities with climate policy. Both climate and sulfur dioxide (SO_2) policies affect the demand for and hence extraction paths of nonrenewable resources. We focus on the power plants' choice between high- and low-sulfur coal in the presence of the announced nation-wide cap on SO_2 emissions that was part of Title IV (the Acid Rain Program). This choice fuel switching between a relatively clean and dirty fuel, parallels the trade-off that exists in a cap-and-trade program for greenhouse gases, such as the European Union Emission Trading Scheme (EU ETS). In addition, the implementation lag of the cap and trade system of Title IV – 5 years for power plants that were subject to Phase I of the cap-and-trade system; 10 years for plants under Phase II – is in line with implementation lags that are relevant in the context of climate policy: the Kyoto Protocol was signed in late 1997, entered into force in 2005, and its first commitment period started in 2008; the EU ETS was first announced in 2001, had a 'pilot' phase in 2005-2007, and started in 2008 (Ellerman, Convery, and de Perthuis, 2010). Insights from the implementation lag of the Acid Rain Program may therefore be useful to policymakers contemplating future climate policies, especially given the pressure on notably the U.S. and China to start curbing their emissions soon.

Although the theory suggests that the green paradox can be tested for using data on resource scarcity rents before and after the announcement of the policy, those rents are unobservable in practice. Not only are sales of proven reserves infrequent, in addition, extraction, milling and refining usually take place in vertically integrated firms (Krautkraemer, 1998; Slade and Thille, 2009). Since the costs of those processes are usually proprietary information, it is hard to derive those rents from data on reserve sales or resource prices, which usually include the costs of these processes (Krautkraemer, 1998; Slade and Thille, 2009). However, the green paradox is based on the effect of the policy on emissions. Our empirical analysis is based on two testable hypotheses regarding the input choice of power plants which in turn can directly be linked to emissions. We derive the hypotheses from a theoretical model in which SO_2 emissions stem from the use of nonrenewable resources that differ in their sulfur content. In this model, emissions are subject to a cap-and-trade scheme from a known future date onward. The implementation lag gives resource owners scope to change their supply behavior before the cap becomes enforced. In particular, we derive hypotheses stating that it is optimal to increase energy input and to shift to high-sulfur coal in the period between announcement of the cap and its implementation.

We find strong evidence that Phase I plants increased the sulfur content of coal in the period between the announcement and implementation of the SO_2 emissions cap of the Acid Rain Program. However, we find no evidence for a change in total energy input in this period. We conclude that SO_2 emissions in the period between the announcement and implementation of the Acid Rain Program may have been higher than they would have been, had the cap been unexpectedly introduced in 1995. Given the strong similarities between the Acid Rain Program and the existing or proposed cap-and-trade programs for greenhouse gases, we believe that our results provide a warning for future climate policies: policy implementation lags may come at an environmental cost.

In the next section, we briefly describe the electricity market in the U.S. in the 1980s and 1990s, as well as the SO_2 cap and trade program that was part of the 1990 CAAA, and its implementation lag. We then present our analytical model of optimal resource use, in which resources differ in their sulfur content and a cap-and-trade scheme has been announced but not yet introduced. From this model, we derive two hypotheses regarding input use by coal-fired power plants in the U.S. during the period in which it was known that a cap on SO_2 emissions would be implemented at a known future date. In section 4 we discuss our strategies for the empirical testing of the hypotheses, and present the data used in the empirical analysis of section 5. We conclude in section 6.

2 Coal-fired electricity generation in the US, and the SO_2 trading program[1]

Before we present our analytical and empirical models, we first provide a short background of the U.S. electricity sector in the 1980s and 1990s.

Coal-fired power plants have consistently supplied around 50% of the US electricity generation (U.S. EIA, 2010). Due to the oil price increases of the mid-1970s, coal-fired generation capacity increased throughout the 1980s. Since 1990 gas-fired generation has been added, which raised the share of gas to around 15% of total generation capacity.

Power plants were economically regulated by each state, generally with a rate of return regulation so that each plant's output price was set as some fraction above their costs of production. Plants were required to meet the states electricity demand and thus had less choice over when to produce than in a liberalized electricity market. This requirement to produce

[1]Ellerman, Joskow, Schmalensee, Montero, and Bailey (2000) provide an excellent description and analysis of the sulfur dioxide emissions trading program created by Title IV of the 1990 CAAA. Ferrall (1991) describes the policy issues related to the introduction of Title IV.

implied that plants were very concerned with assuring a supply of fuel. This concern was heightened for coal-fired power plants as they are often baseload plants in an electricity system. Baseload plants are utilized at all hours of the day because they are relatively low cost to operate and/or they are difficult to stop and start. Nuclear power plants are also often baseload, while natural gas plants tend to be used at peak demand times.

The concern over fuel supply meant that a large majority of coal transactions occurred under long-term forward contracts between plants and coal mines. The contracts were quite complex with many provisions to protect against the hold-up problem. Joskow (1985, 1990) has shown that these contracts are largely adhered to even in the face of changes in spot market coal price and regulation. The average duration of contracts was about 10 years throughout the 1980s and 1990s, though it was decreasing over time (Lange and Bellas, 2007). The decreased duration was also accompanied by an increase in spot market transactions from 10% to 20% of all transactions. The largest increase in spot market activity came from the Western coal basin (Kozhevnikova and Lange, 2009). One reason for the increase may be railroad deregulation which began in the mid-1980s. The real prices for shipping coal by rail fell considerably in the late-1980s and 1990s.

Coal-fired power plants were not only regulated for economic reasons, but also for environmental reasons, as the burning of coal causes the emission of pollutants such as SO_2 and NO_X. U.S. federal regulation of SO_2 emissions from coal-fired plants began with the 1970 CAAA, under which a vintage differentiated emission standard was employed. The 1977 CAAA tightened restrictions on new plants, however this induced owners of power plants to extend the lifetime of existing boilers and resulted in a slower reduction in SO_2 emissions than policymakers had hoped for (Stavins, 2006). The Bush Administration introduced a clean air proposal, including an SO_2 trading program, in the summer of 1989. In Phase I of this program, 263 generating units with an emission rate larger than or equal to 2.5 pounds of SO_2 per million Btu of heat input (lb/mmBtu) in 1985 were granted emission allowances of about 2.5 lb/mmBtu at baseline 1985-87 fuel use (Ellerman, Joskow, Schmalensee, Montero, and Bailey, 2000). Each emission allowance allows its holder to emit one ton of SO_2 in a particular year or any subsequent year. Phase II covered all units with an emission rate of 1.2 lb/mmBtu or higher in 1985 and a capacity of at least 25 MW. Phase II units were to receive allowances at an emission rate of 1.2 lb/mmBtu. The proposal went through the several steps of legislation in 1989 and 1990. The Acid Rain Program required firms to deliver valid allowances to the U.S. Environmental Protection Agency within thirty days after the end of the year. For each ton of emissions that was not covered, the firm has to pay a penalty of $2,000. Allowances that are not needed in any year may be banked for future use, but allowances cannot be borrowed from the future.

The version signed into law by President Bush on November 15, 1990, contained as starting date for Phase I January 1, 1995, and for Phase II January 1, 2000. Depending on what can be considered as the date at which it became clear to owners of high-sulfur coal that a cap SO_2 emissions would be implemented in the future, this gave Phase I units about 4 years to benefit from any changes in equilibrium coal prices that occurred in response to the announcement of the cap.

Plants that were subject to Phase I were previously unregulated at the federal level and generally emitted sulfur dioxide at a much higher rate than the rest of the plants. Emissions standards that applied to them at the state level were generous and usually non-binding constraints (Ackerman and Hassler, 1981). Those plants that were not subject to Phase I were generally subject to regulations set down in earlier versions of the CAA. Some plants not in Phase I were federally regulated by an emissions standard while other were federally regulated by an implicit technology standard.

3 Policy announcements and green paradoxes: a theoretical framework

We present a stylized model of exhaustible resource use, in the presence of announced environmental policy.[2] Our aim is to capture the key features of Title IV of the Clean Air Act Amendments of 1990, which introduced SO_2 emissions trading for coal-fired power plants in the continental United States, and to derive testable hypotheses regarding coal input in the period between the announcement of the emissions cap and its implementation. The model features two exhaustible resource stocks, that differ in their polluting intensity (low and high-sulfur coal). The two extraction sectors are perfectly competitive and supply their coal to a competitive electricity sector. A cap on sulfur dioxide emissions is announced at $t = 0$ and becomes effective at $t = T > 0$. From this instant onwards, firms in the electricity sector must surrender an emission permit for each unit of emissions. Permits are freely tradable between firms.

Mining firms own two distinct stocks of coal, whose initial levels $S_H(0) = S_{H0}$ and $S_L(0) = S_{LH0}$ are given and known with certainty. Resource extraction depletes the stock according to,

$$\dot{S}_i(t) = -R_i(t) \qquad i \in \{H, L\}; \tag{1}$$

and in each sector the representative firm chooses extraction $R_i(t)$ such that it maximizes its profits. Both the stocks and the extraction flows of each resource are expressed in units of energy. For simplicity, we assume that the extraction of both types of coal is characterized by the same, constant marginal costs. Without loss of generality, we assume the marginal extraction cost to be equal to zero.

Electricity generators use coal to generate electricity η, which they sell to final consumers. They are indifferent between the two types of coal:

$$\eta(t) = R_L(t) + R_H(t). \tag{2}$$

Final consumers derive utility directly from their energy consumption. Given (2), this is equivalent to assuming that utility is derived directly from resource use. The instantaneous utility function, $U(\eta)$, is assumed to be a $\mathcal{C}^2$ function with $U' > 0$ and $U'' < 0$, which satisfies the Inada conditions. The representative consumer maximizes the present value of her lifetime utility taking the market price of eelectricity as given.

The market price of each type of coal depends on its scarcity and, in the presence of emissions trading, on the price of the allowances necessary to cover the associated emissions of SO_2. Each year a new vintage of allowances is issued; as a consequence, emitting firms cannot submit allowances of future vintages to cover current emissions (i.e. borrowing is not allowed). Firms are allowed, however, to reduce their emissions and keep any excess permits for future use (banking). In our analytical model, we disregard the second enforcement phase and model the policy as an announced ceiling on emissions that cannot be exceeded from the time of implementation $t = T > 0$ onwards.

[2]The model is based on the model used in Di Maria, Smulders, and Van der Werf (2008).

The complete model reads:

$$\max_{\{R_H(t),R_L(t)\}_0^\infty} \int_0^\infty U(\eta(t))\,\mathrm{e}^{-\rho t}\mathrm{d}t \tag{1.a}$$

$$\text{s.t.}\quad \eta(t) = R_H(t) + R_L(t); \tag{1.b}$$

$$\dot{S}_H(t) = -R_H(t),\ R_H(t) \geq 0,\ S_H(0) = S_{H0}; \tag{1.c}$$

$$\dot{S}_L(t) = -R_L(t),\ R_L(t) \geq 0,\ S_L(0) = S_{L0}; \tag{1.d}$$

$$Z(t) \equiv \varepsilon_H R_H(t) + \varepsilon_L R_L(t) \leq \bar{Z}\ \forall t \geq T. \tag{1.e}$$

Parameter ρ is the rate of time preference. Equations (1.c) and (1.d) describe the dynamics of the resource stocks. Environmental policy is described in (1.e). Emissions (Z) arise from resource use, in that the use of one unit of $i \in \{H, L\}$, entails the emission of ε_i units of SO_2, with $\varepsilon_H > \varepsilon_L$. From $T > 0$ onwards, total emissions are constrained not to exceed $\bar{Z}$. This entails the division of the planning horizon into two phases: an interim phase during which the constraint is not yet enforced, and an enforcement phase when the constraint begins to bind the agents' actions. The problem presented above is an infinite-horizon discounted two-stage optimal control problem, with a fixed switching time (at $t = T$). During the interim phase, the consumption and extraction paths must be chosen to maximize the present discounted value of utility over this phase, and leave an optimal amount of the two resources for the second stage. During the second stage, consumption and extraction must be chosen to maximize discounted utility over the remaining horizon, given the resource stock at the time of enforcement T.

The Lagrangians for the two stages of the problem are:

$$\mathcal{L}^I(\cdot) = U(\eta(t)) - \sum_{i\in\{H;L\}} \lambda_i^I(t)R_i(t) + \sum_{i\in\{H,L\}} \gamma_i^I(t)R_i(t); \tag{2}$$

$$\mathcal{L}^E(\cdot) = U(\eta(t)) - \sum_{i\in\{H;L\}} \lambda_i^E(t)R_i(t) + \sum_{i\in\{H,L\}} \gamma_i^E(t)R_i(t) + \tau(t)\left(\bar{Z} - Z(t)\right); \tag{3}$$

where superscript I indicates the Lagrangian for the interim phase, i.e. $\forall t \in [0, T)$, while E indicates the Lagrangian for $t \geq T$, the enforcement phase. The λ_i's are the co-state variables associated with (1.c) and (1.d), the γ_i's the multipliers for the nonnegativity constraints on the extraction rates, and τ is the multiplier associated with the emission constraint.

The necessary conditions for the optimum extraction paths are:[3]

$$U'(\eta(t)) = \lambda_i^j(t) - \gamma_i^j(t) + \varepsilon_i \tau^j(t) \equiv p_i(t), \tag{4}$$

$$\dot{\lambda}_i^j(t) = \rho\lambda_i^j(t); \tag{5}$$

with $i \in \{H, L\}$ and $j \in \{E, I\}$.

Given that there are no discontinuities in the resource stocks, it is easy to show that the costate variables associated with the resource stocks must be continuous, i.e.

$$\lambda_i^I(T^-) = \lambda_i^E(T^+). \tag{6}$$

Hence, one can conclude that the scarcity rents $\lambda_i(t)$ grow continuously at rate ρ over the entire planning horizon.

[3]In the interest of compactness, we have indicated the necessary conditions for the two stages as one. Note that $\tau^I = 0$.

The complementary slackness conditions for the constraints are,

$$\tau(t) \geq 0,\ \bar{Z} - Z(t) \geq 0,\ \tau(t)\left[\bar{Z} - Z(t)\right] = 0,\ \forall t \geq T; \tag{7}$$

$$\gamma_i^j(t) \geq 0,\ R_i(t) \geq 0,\ \gamma_i^j(t) R_i(t) = 0; \tag{8}$$

and the transversality conditions are,

$$\lim_{t\to\infty} \lambda_i(t) S_i(t)\, \mathrm{e}^{-\rho t} = 0. \tag{9}$$

In the absence of (binding) regulation (i.e. when either $\bar{Z}$ is large enough, or when $T \to \infty$), the model reduces to a simple problem of exhaustible resource extraction à la Hotelling (1931). In this case, given that the two resources are perfectly substitutable in energy generation, they can be treated as one. The optimal extraction path is then one along which the scarcity rent $\lambda(t)$ grows over time at rate ρ, according to the Hotelling rule (5). At each point in time total energy generation equals energy demand, and is simply given by $\eta(t) = d(\lambda(t)) \equiv U'^{-1}(\lambda(t))$. Accordingly, the quantity extracted decreases over time so that marginal utility grows along with the scarcity rent – see (4). In this model it never pays to leave resources unexploited, hence the initial value of the scarcity rent, $\lambda_0 \equiv \lambda(0)$, must solve $\int_0^\infty d\left(\lambda_0 \mathrm{e}^{\rho t}\right) \mathrm{d}t = S_0$. Since the two resources are indistinguishable as long as their polluting content does not matter, the exact composition of extraction is undetermined along the unconstrained path, and so is the sulfur intensity of energy. We use this situation of 'laissez faire' as our benchmark, against which we compare the results of the announcement and introduction of the cap-and-trade program.

The announcement at $t = 0$ of a cap on sulfur dioxide emissions from $t = T > 0$ onward has the following effects on coal use, relative to the case of laissez-faire:

Proposition 1. *If, in the economy described by* (1)-(9)*, the announced constraint is binding over some period of time, then:*

i. The level of energy use $\eta(t)$ exceeds the level prevailing in the laissez-faire economy at any point in time in the period before the cap and trade program becomes enforced;

ii. Provided that S_{H0} is large enough, only the high-sulfur fuel will be used before the cap and trade program becomes enforced.

Proof. See Appendix A. □

This outcome arises from two distinct effects of the announcement of the emissions cap. On the one hand, the regulation makes both resources more abundant outside the period in which the cap is binding. In our model of physical exhaustion, the mere fact that extraction is reduced over some period of time due to the cap on SO_2 emissions creates incentives for the resource owners to extract more when the economy is not constrained. In equilibrium, the scarcity rents fall, and energy use increases relative to the case of 'laissez faire' – an effect we denote the *abundance effect*. On the other hand, when the high-sulfur resource is abundant relative to the cleaner resource, the latter becomes much more useful during the period in which the cap is binding than at other points of time.[4] This is because more energy can

[4] Ideally, along a constrained path, one would want to use only the clean fuel as long as the constraint is binding, as it gives a higher level of energy per unit of emissions. Prior to enforcement, and after the constraint ceases to be binding, the dirty fuel can be used without reducing the amount of energy being available. Thus, 'relatively abundant' in this context means that the stock of H is so large that it is not possible to use up all of it ahead of implementation and during the last phase (when the constraint does not bind any more) of the extraction path. A formal discussion of this aspect is contained in Appendix A below.

be produced with the clean fuel for a given level of emissions. Hence, the cleaner resource becomes relatively scarcer than the dirtier one, leading to an *ordering effect*: the scarcity rent of the dirtier fuel falls relatively more than that of the cleaner one, and high-sulfur coal becomes the preferred fuel at any instant at which the constraint does not bind. To summarize, in the period before the cap and trade program, not only are more resources used as a consequence of the announcement, but there is also a shift towards the most polluting fuel. Both effects induce an increase in SO_2 emissions.

Despite its stylized nature, this theoretical model provides us with two testable implications regarding the effect of the announcement in 1990 of the Acid Rain Program on total fuel input and SO_2 emissions:

(P1) In the period between the announcement and the enforcement of the cap and trade program, total resource use tends to increase;

(P2) In the period between the announcement and the enforcement of the cap and trade program, the dirtier resource tends to become the preferred energy source, inducing an increase in SO_2 emissions per unit of energy input.

In section 5, we empirically test these hypotheses with data on the use of coal with varying degree of sulfur intensity by U.S. power plants.

4 Empirical strategy and data

4.1 Empirical model

Hypothesis P1 states that the total energy input of Phase I coal-fired power plants increased, following the announcement of the cap on SO_2 emissions of the Acid Rain Program. Hypothesis P2 states that the sulfur content of energy input of Phase I coal-fired power plants increased, following the announcement. We will use difference-in-difference analyses using monthly plant-level panel data to test these hypotheses. Our basic regression equation is

$$y_{j,t} = \beta_{0,j} + \beta_{1,n} + \beta_2 \text{Interim}_t + \beta_3 \text{Interim}_t * \text{PhaseI}_j + \beta_4 \text{Implement}_t + \mathbf{x}_j' \boldsymbol{\alpha} + \epsilon_{j,t} \tag{10}$$

where y is the respective dependent variable, j indicates the plant, t indicates a particular month in a particular year, n indicates a particular year, the βs are coefficients to be estimated – where $\beta_{0,j}$ are plant-specific intercepts and $\beta_{1,n}$ is a year dummy –, $\boldsymbol{\alpha}$ is a vector of coefficients to be estimated, and ϵ is an IID error term. 'Interim' is a dummy variable equal to one for any month in the period between the announcement and implementation of the SO_2 cap and trade program, and 'PhaseI' is a dummy variable equal to one for all plants that (mandatory and voluntarily) participated throughout the entire period in Phase I and is zero otherwise. The interaction of these variables is our difference-in-differences variable: coefficient β_3 indicates the difference in behavior between Phase I plants and the average plant (which is made up of both Phase I and Phase II plants). 'Implement' is a dummy equal to one for each month in which the program was implemented. The vector $\mathbf{x}_j$ indicates a vector of control variables.

In our difference-in-difference analysis, Phase I plants are the treated group while the announcement period is the period when the treatment applies. A positive coefficient for the interaction between interim period and Phase I plant and a negative coefficient for the dummy variable representing the implementation period would support our hypotheses P1

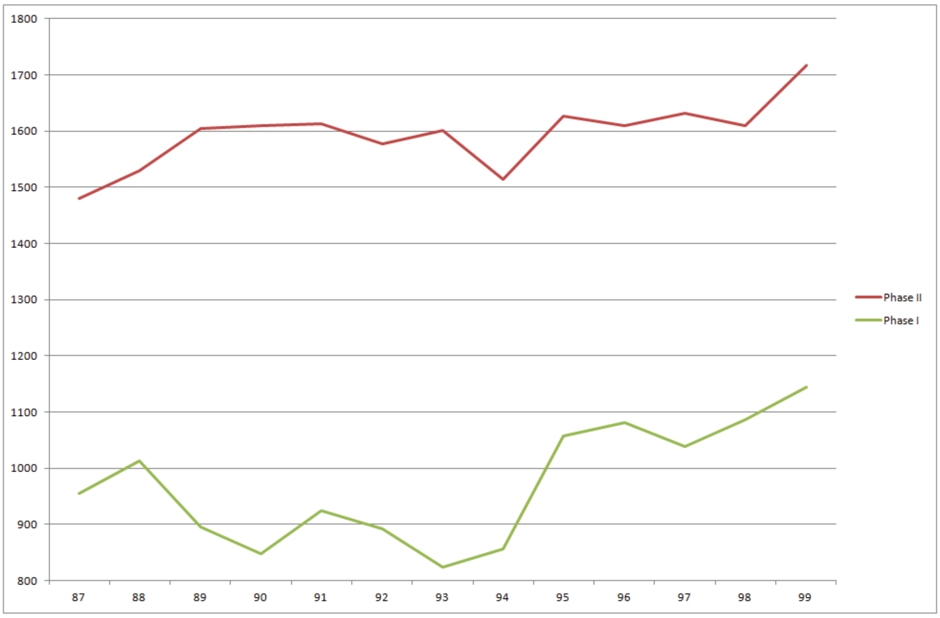

Figure 1: *Yearly average of average monthly heat input at the plant level, mmBtu.*

and P2. The interaction term reveals whether the Phase I plants bought more heat (abundance hypothesis P1) or coal with higher sulfur content (ordering hypothesis P2) than the non-Phase I plants during the period December 1990 - December 1994. A negative coefficient for the implementation dummy would imply that, on average, all plants reduced their purchase of total heat/sulfur intensive coal from January 1995 until the end of the sample.

The control group we utilize are plants which are to be regulated in Phase II of the Acid Rain Program. Phase II plants were to be brought under the Acid Rain Program in 2000, ten years after the law was passed. While Phase I plants were not randomly decided upon, there is good evidence that Phase II plants were unaffected by the interim period of the Acid Rain Program. For P1, Figure 1 shows that Phase II plants' heat input does not show any pattern that is inconsistent with being a control group. Their average heat input is stable across the interim period. In terms of P2, Phase II plants are generally regulated with an emissions standard from the 1970 or 1977 CAAA, making it impossible for them to increase their sulfur intensity. Furthermore, the standard is equivalent to the rate at which permits were allocated in the Acid Rain Program. Hence they had little scope to increase their emissions rate.

4.2 Control variables included for hypothesis P1.

To test the first hypothesis, that total energy use increased in the period between the Acid Rain Program's announcement and its implementation, dependent variable $y_{j,t}$ is the total heat input (in billions Btu) of plant j in month t. It is collected from a panel dataset from the U.S. Federal Energy Regulatory Commission, FERC, via form FERC-423 'Monthly Cost and Quality of Fuels for Electric Plants'. The Form collects monthly information on the cost and quality of coal deliveries to plants of 50 MW or larger capacity. The dataset records both deliveries made as part of long-term contracts, and deliveries that originate from spot purchases on the market. We use information for the period 1987-1999 to construct the total heat content (in billion Btu) of coal purchased as the dependent variable. This time period starts three years before the 1990 CAAA was passed and extends through Phase I. The sample of plants in FERC-423 shrinks after 1999 as plants in restructured electricity markets are dropped by the FERC. The sample begins in 1987 to avoid including the changing structure of the coal market in the pre-policy period. As discussed in Ellerman and Montero (1998) and Kozhevnikova and Lange (2009), a larger share of coal was coming from the Western coal basin and transacted in the spot market by 1987 relative to earlier in the decade.

In our base regression, the interim period runs from December 1990 to December 1994, so we take the signing into law of the 1990 CAAA in November 1990 as the instant of announcement of the SO_2 cap and trade program. Our implementation phase variable takes the value one from January 1995 onward.

For the first hypothesis, our vector of controls consists of the variables 'State Industrial Activity', 'Gas price', 'Scrubber', 'Summer' and 'Winter'. We use the Coincident Economic Activity Index of the Federal Reserve Bank of St. Louis to control for business cycle effects and industrial activity at the state level. The monthly index includes nonfarm payroll employment, the unemployment rate, average hours worked in manufacturing and wages and salaries.[5] We use the gas price to control for changes in the market for natural gas and the fact that gas is a substitute fuel for electricity production. The data are taken from U.S. EIA (2010) and are in U.S. dollar cents per thousand cubic feet and are discounted using the PPI for crude energy to 1982 dollars. 'Scrubber' is a dummy variable equal to one in each month in which a plant had a flue gas desulfurization unit (SO_2 control equipment, also known as a 'scrubber') installed. It is constructed using data from the EIA Form 767. The summer dummy equals one during the months June, July, August and September and is zero otherwise. The winter dummy equals one during the months December, January, February and March and is zero otherwise. Descriptive statistics of all variables are provided in Table 1.

To test for the robustness of the results of the base regression, we run a regression with the sample restricted to plants in states that have Phase I plants in their borders. The sample restriction ensures that the treatment and control groups are similar geographically for our difference-in-difference analysis. Secondly we present results of a 'triple difference-in-difference analysis', in which we use plants in states with nuclear plants as an additional control group. The presence of nuclear power plants makes it harder for coal-fired power plants to expand their electricity supply, since both types of plants are typically used as baseload capacity. Furthermore we run a regression with the interim period starting in June 1989 (when the Bush administration announced its clean air proposal in general terms).

In addition, we perform a time series analysis for the ratio of coal-fired generation to total electricity generation in million kWh in the U.S., for the period 1987-1999. The data for this variable are collected from the Annual Energy Review, which is published by the U.S. Energy Information Administration (U.S. EIA, 2005). Figure 2 shows the evolution of this ratio over time. In the time series analysis, lags of the coal to total generation ratio are included, as well as our dummy variables for the interim and implementation periods, the change in industrial activity, the ratio of gas to total generation, and seasonal dummies. In addition, two trend variables are created to control for the patterns displayed in Figure 2. The data show two trends, an increasing trend in the 1980s and a flat or slightly decreasing trend afterwards. An early trend variable takes the value of one in January 1987 and increases by one each month until January 1990 when the variable becomes zero for the rest of the sample. An early trend squared variable is created by multiplying the early trend by itself. This was done because residual graphs and tests reveal cycles in the first part of the dataset that were not controlled for with a linear trend. A late trend variable takes the value of one in January 1990 and increases by one each month until the end of the sample. It is set to zero

[5]State-level GDP data are only available from 1997 onwards.

Table 1: Descriptive statistics

Sample	All Transactions	Before 1990 CAAA	After 1990 CAAA	Phase I	Non Phase I	Non Phase I in PhI State
Variable	Mean (S.D.)	Mean (S.D.)	Mean (S.D.)	Mean (S.D.)	Mean (S.D.)	Mean (S.D.)
Sulfur intensity (lbs/mmBtu)	1.17	1.28	1.12	1.55	0.97	1.18
	(0.82)	(0.88)	(0.82)	(0.87)	(0.75)	(0.88)
Total heat (billions of Btu)	1391.37	1341.76	1412.89	978.13	1607.30	868.67
	(2192.70)	(2207.00)	(2186.05)	(1319.45)	(2504.94)	(1348.27)
State Coincident Economic	99.39	99.14	99.62	97.09	100.76	100.10
Activity Index (July 1992 = 100)	(23.40)	(23.23)	(23.47)	(23.54)	(23.22)	(23.42)
Gas Price (cents per 1000 cubic ft)	343.85	312.42	357.49	343.45	344.06	344.12
	(44.16)	(52.87)	(31.12)	(44.48)	(43.99)	(44.06)
Coal to total electricity ratio						
Rail price (mills per ton-mile)	19.53	25.38	16.99	19.61	19.49	19.51
	(4.73)	(3.16)	(2.54)	(4.76)	(4.71)	(4.72)
Plant w/ scrubber	0.10	0.03	0.13	0.05	0.12	0.11
	(0.31)	(0.17)	(0.33)	(0.22)	(0.32)	(0.32)
Interim period	0.31					
	(0.46)					
Implementation period	0.38					
	(0.48)					
Phase I	0.34					
	(0.47)					
Summer months	0.34					
	(0.47)					
Winter months	0.32					
	(0.46)					
Close to PRB						

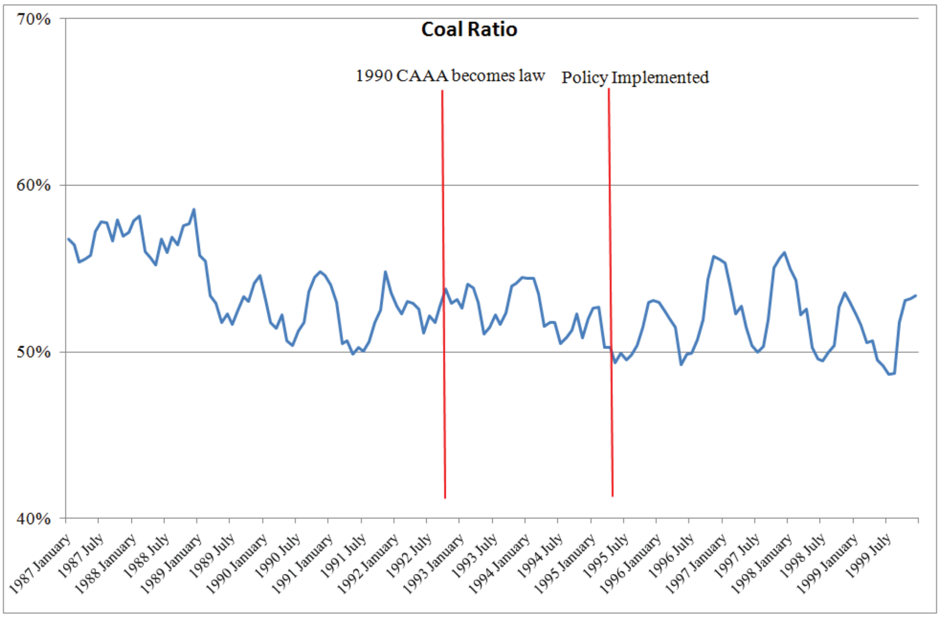

Figure 2: *Ratio of coal-fired generation to total electricity generation.*

for months previous to January 1990. Summer and winter seasonal dummies are included as well. The change in industrial production variable is created by taking the first difference of the Coincident Economic Activity Index. When electricity demand is low, plants with higher marginal costs (often oil or gas generation) are not used and the ratio of coal to total generation increases. The ratio of gas generation to total generation is calculated from the EIA Annual Energy Review.

4.3 Control variables included for hypothesis P2.

To test our second hypothesis (that dirtier coal types became the preferred input in the period between the cap's announcement and its implementation) we use the sulfur content of coal delivered as the dependent variable. The data are obtained from FERC-423. In our base regression, we use the same starting and end-dates of the interim and implementation period as in the base regression for the first hypothesis. Our vector of controls consists of the variables 'Scrubber', 'Rail Price', a dummy variable equal to one if the plant is located in a state about 400-1200 miles from the Powder River coal basin (PRB), and an interaction term for 'Rail Price' and the latter variable. The rail rates variable 'Rail Price' is created with data from the EIA (U.S. EIA, 2004) on the average rate per ton-mile per year. The variable 'Close to PRB' is equal to one if the state is roughly in the 400-1200 miles range from the Powder River Basin. This basin has the lowest sulfur content of the big basins, while the Interior coal basin has the highest sulfur content and coal from the Appalachian basin has a sulfur content between that of the PRB and Interior basins. Ellerman and Montero (1998) showed that the declining rail transport prices in the 1980s and 1990s changed the economics of coal choice in favor of the Powder River Basin for power plants in a range of 400-1200 miles from the PRB.[6]

To test for the robustness of the results of the base regression, we again ran a regression with

[6]We include the following states in the variable 'Close to PRB': Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Michigan, Minnesota, Missouri, Nebraska, Oklahoma, Texas, Washington and Wisconsin.

the sample restricted to spot market transactions for plants in states that have Phase I plants in their borders. In addition we present results for a regression with the sulfur intensity of each transaction as dependent variable and the sample restricted to transactions on the spot market only. Most coal delivered has been agreed upon in long-term contracts. As discussed in Joskow (1988, 1990), plants are limited in how they can alter their coal purchases within a contract when conditions in the coal market change. Indeed, as argued by Carlson, Burtraw, Cropper, and Palmer (2000), long-term contracts may prevent utilities to respond to price changes when it appears to be economic for them to do so. Thus, it is expected that an ordering effect is more likely to be seen in the spot market. In the final test for the robustness of our results we let the interim period start in June 1989 and end in December 1994.

5 Empirical analysis

5.1 Hypothesis P1: the abundance effect

To test hypothesis P1 which states that total resource use increased after announcement of the SO_2 emissions cap, we estimate a difference-in-difference fixed plant effects model, with total heat delivered per month for each plant as the dependent variable. Explanatory variables are dummies for the implementation phase of the cap, for summer and winter months, and for plants with a scrubber, as well as a gas price variable and an index for state industrial activity. The results are presented in Table 2. Our baseline regression does not confirm hypothesis P1: the parameter of our difference in difference variable 'Interim Period * Phase I' does not differ from zero at an acceptable statistical significance level and even has the wrong sign. Indeed, the only variable with a statistically significant coefficient is the variable for summer months. The results of our robustness checks based on our panel data model do not differ much from this pattern.

As an additional robustness check for the results of the test for hypothesis P1 we employ a time series analysis of the ratio of coal generation to total generation. A number of different lag combinations were used to control for serial correlation in the data. The best fit came from using lags of 1, 3, 6, 10, 12 and 15 months. For the model given in Table 3, two tests, Portmanteau Q and Bartlett's Periodogram, fail to reject that the residuals are white noise. Thus we conclude that the model is properly specified. The dummy for the interim period is statistically insignificant, so based on our time series analysis we cannot confirm that the existence of a period between the signing into law of the 1990 CAAA and the start of the first phase of the SO_2 cap and trade program induced an increase in heat input by coal-fired power plants. Altering the interim period to start in June 1989 (when the Bush administration announced its clean air proposal in general terms) does not alter the results.

Empirically there is no support for the abundance hypothesis: Phase I plants did not seem to increase their heat input in response to the announcement of the SO_2 emissions cap of the 1990 CAAA. A first possible reason for this is that the price inelasticity of demand for electricity implies a small change in demand and (hence) output when prices fall. A second reason is that since coal plants are often baseload plants (or low on the load curve) they would have little ability to increase production and were likely already running at full capacity before the announcement of the 1990 CAAA.

Table 2: Hypothesis P1, the abundance effect: panel data analysis

Dependent Variable	Total heat purchased	Total heat purchased	Total heat purchased	Total heat purchased
Sample	All transactions	All transactions for plants in states with Phase I plants	All transactions	All transactions
Interim Period	13.71	−19.10	13.69	
	(42.71)	(49.70)	(42.91)	
Interim Period * Phase I	−87.26	−19.72	−67.65	
	(60.08)	(61.70)	(55.60)	
Interim Period * No Nuclear			−78.37	
			(125.26)	
Long Interim Period				−87.37*
				(51.98)
Long Interim Period * Phase I				−43.73
				(56.16)
Implementation Period	103.55	56.60	103.39	−18.66
	(72.18)	(74.41)	(72.24)	(56.82)
State Industrial Activity	−0.80	−0.40	−0.80	−0.43
	(0.50)	(0.40)	(0.50)	(0.38)
Gas Price	0.15	0.41	0.16	0.35
	(0.24)	(0.30)	(0.24)	(0.29)
Plant w/ Scrubber	−160.60	61.96	−160.60	65.45
	(154.23)	(111.99)	(145.23)	(113.17)
Summer Months	59.86**	17.43	59.87**	19.04
	(29.82)	(14.19)	(29.82)	(14.03)
Winter Months	28.05	−4.65	28.06	−7.87
	(18.64)	(18.34)	(18.64)	(18.10)
Observations	56,726	40,001	56,726	40,001
Plants	403	289	403	289

Notes: Fixed plant effects. Year dummies not shown for brevity. Time period is Jan. 1987-Dec. 1999.
*, **, *** indicate 10%, 5% and 1% statistical significance, respectively.
Standard Errors corrected for panel serial correlation in parentheses.

5.2 Hypothesis P2: the ordering effect

We estimate a difference-in-difference fixed plant effects model to test for an ordering effect. The choice of sulfur intensity of coal delivered is a function of the policy period when the transaction was made (pre-announcement period, interim period or implementation period), an interaction of the interim period and the Phase I dummy, whether the plant has a scrubber, the rail price, and the rail price interacted with a dummy equal to one if the plant is roughly located in the 400-1200 mile range from the Powder River Basin, and year dummies.

The second column of Table 4 presents results of our baseline regression. The coefficient to the variable Interim Period suggests that, on average, coal-fired power plants reduced their sulfur content in the period 1991-1994. This is in line with the general trend in the coal market due to the expansion of the Western coal basin. This expansion was not only due to increased demand in the Midwest due to falling rail transport costs (Ellerman and Montero,

Table 3: Hypothesis P1, the abundance effect: time series analysis

Dependent Variable	Ratio of Coal to Total Generation
Interim Period	$-1.8E-04$
	$(2.6E-03)$
Implementation Period	$5.4E-03$
	$(6.1E-03)$
Change in Industrial Activity	0.01
	(0.01)
Ratio of Gas to Total Generation	0.02
	(0.04)
Observations	141

Notes: Time period is 1981-2002.
*, **, *** indicate 10%, 5% and 1% statistical significance, respectively.
Heteroskedasticity correct standard errors in parentheses.
Both the Portmanteau Q and Bartlett's Periodogram test fail to reject that the residuals are white noise. Lags included are 1, 3, 6, 10, 12 and 15 months.
A linear trend and a squared trend for the 1980s and a linear trend for the post-1980s, along with winter and summer dummies are also included.

1998), but also due to strong productivity increases and economies of scale at Western coal mines (U.S. EIA, 1999). Our variable of interest is the interaction between Interim Period and the dummy for Phase I plants. The positive and significant coefficient suggests that Phase I plants increased their sulfur content in the period between the announcement and the implementation of the cap of the 1990 CAAA, relative to Phase II plants. Note that the latter group of plants had very little scope to increase their sulfur content due to the maximum emission rates that were included in the 1970 and 1977 Clean Air Act Amendments. Hence it seems that a green paradox indeed occurred in response to the announcement of the SO_2 emissions cap of the Acid Rain Program. As expected, sulfur content was lower after the cap got implemented, plants with flue gas desulfurization units bought coal with higher sulfur content, and plants located 400-1200 miles from the Powder River Basin tended to buy cleaner coal when rail transport costs were low.

Our robustness checks confirm these results. Restricting the sample to plants that are located in states that have Phase I plants within their borders increases the (absolute value of) the coefficients and still shows an increase in sulfur content of coal delivered to Phase I plants in the interim phase. The fourth column of Table 4 presents the results of the regression for the sulfur intensity of coal delivered through transactions on the spot market. The results are similar to the ones in the previous columns. As a final robustness check we extended the interim phase from December 1990-December 1994 to June 1989-December 1994. This still gives similar results.

Our results indicate that Phase I plants increased the sulfur content of their coal in the period between the announcement and the implementation of the cap on sulfur dioxide emissions that was part of the Acid Rain Program. Relative to non Phase I plants, which had little scope to increase their sulfur intensity due to pre-existing regulation, Phase I plants increased their sulfur content with 0.08 to 0.18 pounds per million Btu, against an average of 1.55 pounds per million Btu for Phase I plants: an increase of 5 to 12%.

Table 4: Hypothesis P2, the ordering effect

Dependent Variable Sample	Sulfur intensity All transactions	Sulfur intensity All transactions for plants in states with Phase I plants	Sulfur intensity Spot transactions	Sulfur intensity All transactions
Interim Period	-0.04^{***}	-0.06^{**}	-0.07^{**}	
	(0.01)	(0.02)	(0.03)	
Interim Period * Phase I	0.11^{***}	0.13^{**}	0.08^{*}	
	(0.03)	(0.03)	(0.04)	
Long Interim Period				-0.06^{**}
				(0.02)
Long Interim Period * Phase I				0.18^{***}
				(0.04)
Implementation Period	-0.06^{***}	-0.08^{***}	-0.09^{***}	-0.05^{**}
	(0.02)	(0.02)	(0.03)	(0.02)
Plant w/ Scrubber	0.08^{**}	0.14^{**}	0.08	0.07^{**}
	(0.04)	(0.05)	(0.06)	(0.03)
Rail Price	0.03	0.05	0.05	0.03
	(0.02)	(0.03)	(0.05)	(0.03)
Rail Price * Close to PRB	0.02^{**}	0.03^{**}	0.02^{**}	0.02^{**}
	(0.01)	(0.01)	(0.01)	(0.01)
Observations	56,726	40,001	17,946	56,726
Plants	403	289	371	403

Notes: Fixed effects are plant fixed effects.
Year dummies not shown for brevity. Time period is Jan. 1987-Dec. 1999.
*, **, *** indicate 10%, 5% and 1% statistical significance, respectively.
Standard Errors corrected for panel serial correlation in parentheses.

6 Concluding remarks

A recent surge in the literature on suboptimal climate policy has provided several conditions under which such a policy in theory could lead to detrimental environmental outcomes (a 'green paradox'). In this paper, we have taken the theory to the data. One of the mechanisms through which environmental policy could lead to an increase in harmful emissions is through the response of suppliers of nonrenewable resources in the presence of an implementation lag for the policy. We have argued that the implementation lag of the SO_2 trading program of the 1990 CAAA has strong parallels with the implementation lags of climate policies. We have derived two testable hypotheses from a theoretical model of the optimal use of high- and low-sulfur coal in the presence of an implementation lag for a cap on SO_2 emissions. The first hypothesis states that (Phase I) coal-fired power plants increased their heat input in the period between announcement of the emissions cap and its implementation. The second hypothesis states that those plants increased the sulfur content of the coal used. Ceteris paribus, each mechanism would induce an increase in SO_2 emissions.

We use data on coal use by U.S. coal-fired power plants to test these hypotheses in the context of the SO_2 trading program of the 1990 CAAA. We do not find evidence for the first hypothesis: coal-fired power plants seem not to have changed their heat input in response to the announcement of the sulfur dioxide emissions cap of the Acid Rain Program. Regarding the second hypothesis (ordering effect), we find robust evidence that plants that were subject to Phase I increased the sulfur content of the coal used in the period between the announcement and implementation of the cap. Relative to non Phase I plants, they increased their sulfur intensity with 5 to 12%.

Although our results regarding the existence of a green paradox are mixed, they do suggest that the existence of an implementation lag for environmental policy, in the context of emissions from the use of nonrenewable resources, may induce unintended and detrimental behavioral changes by resource owners and electricity generators. Given the strong similarities between the implementation lag of the SO_2 cap and trade program in the U.S. and the implementation lag of existing and possible future climate policies, policy makers should take into account the possible emissions increase in response to a policy implementation lag.

References

ACKERMAN, B., AND W. HASSLER (1981): *Clean Coal/Dirty Air*. Yale University Press, New Haven, CT.

CARLSON, C., D. BURTRAW, M. CROPPER, AND K. PALMER (2000): "Sulfur Dioxide Control by Electric Utilities: What Are the Gains from Trade?," *Journal of Political Economy*, 108(6), 1292–1326.

DI MARIA, C., S. SMULDERS, AND E. VAN DER WERF (2008): "Absolute Abundance and Relative Scarcity: Announced Policy, Resource Extraction, and Carbon Emissions," FEEM Working Paper 92.2008.

EICHNER, T., AND R. PETHIG (2011): "Carbon leakage, the green paradox and perfect future markets," *International Economic Review*, 52(3), 767–805.

ELLERMAN, A. D., F. J. CONVERY, AND C. DE PERTHUIS (2010): *Pricing Carbon: the European Union Emissions Trading Scheme*. Cambridge University Press, Cambridge, MA.

ELLERMAN, A. D., P. L. JOSKOW, R. SCHMALENSEE, J.-P. MONTERO, AND E. M. BAILEY (2000): *Markets for Clean Air: the U.S. Acid Rain Program*. Cambridge University Press, New York.

ELLERMAN, A. D., AND J.-P. MONTERO (1998): "The Declining Trend in Sulfur Dioxide Emissions: Implications for Allowance Prices," *Journal of Environmental Economics and Management*, 36(1), 26–45.

FERRALL, B. R. (1991): "Recent developments: The Clean Air Act Amendments of 1990 and the use of market forces to control sulfur dioxide emissions," *Harvard Journal on Legislation*, 28, 235–252.

GERLAGH, R. (2011): "Too much oil," *CESifo Economic Studies*, 57(1), 79–102.

HOEL, M. (2010): "Is there a green paradox?," CESifo Working Paper 3168.

——— (2011a): "The green paradox and greenhouse gas reducing investments," *International Review of Environmental and Resource Economics*, forthcoming.

——— (2011b): "The supply side of CO_2 with country heterogeneity," CESifo Working Paper 3393.

HOTELLING, H. (1931): "The economics of exhaustible resources," *Journal of Political Economy*, 39(2), 137–175.

JOSKOW, P. (1985): "Vertical Integration and Long-Term Contracts: The Case of Coal-Burning Electric Generating Plants," *Journal of Law, Economics, & Organization*, 1(1), 33–80.

——— (1988): "Price Adjustment in Long-Term Contracts: The Case of Coal," *Journal of Law & Economics*, 31(1), 47–83.

——— (1990): "The Performance of Long-Term Contracts: Further Evidence from Coal Markets," *RAND Journal of Economics*, 21(2), 251–274.

KOZHEVNIKOVA, M., AND I. LANGE (2009): "Determinants of Contract Duration: Further Evidence from Coal-Fired Power Plants," *Review of Industrial Organization*, 34(3), 217–229.

KRAUTKRAEMER, J. A. (1998): "Nonrenewable Resource Scarcity," *Journal of Economic Literature*, 36(4), 2065–2107.

LANGE, I., AND A. BELLAS (2007): "The 1990 Clean Air Act and the Implicit Price of Sulfur in Coal," *The B.E. Journal of Economic Analysis & Policy*, 7(1), Article 41.

SINN, H.-W. (2008): "Public policies against global warming," *International Tax and Public Finance*, 15(4), 360–394.

SLADE, M. E., AND H. THILLE (2009): "Whither Hotelling: Tests of the Theory of Exhaustible Resources," *Annual Review of Resource Economics*, 1(1), 239–259.

SMULDERS, S., Y. TSUR, AND A. ZEMEL (2010): "Announcing climate policy: can a green paradox arise without scarcity?," CESifo Working Paper 3307.

STAVINS, R. N. (2006): "Vintage-differentiated environmental regulation," *Stanford Environmental Law Journal*, 25(1), 29–63.

U.S. EIA (1999): "The U.S. Coal Industry in the 1990's: Low Prices and Record Production," United States Energy Information Administration.

——— (2004): "Coal Transportation: Rates and Trends," United States Energy Information Administration.

——— (2005): "Annual Energy Review," United States Energy Information Administration.

——— (2010): "Annual Energy Review," United States Energy Information Administration.

VAN DER PLOEG, F., AND C. WITHAGEN (2010): "Is there really a Green Paradox?," CESifo Working Paper 2963.

VAN DER WERF, E., AND C. DI MARIA (2011): "Unintended Detrimental Effects of Environmental Policy: The Green Paradox and Beyond," CESifo Working Paper 3466.

A Proof of Proposition 1

Let $S_i(0) = S_{iO}$ be the initial stock of resource $i = H, L$. Then, $\mathbf{S_0} = \{S_{L0}, S_{H0}\}$ is the vector of initial resource stocks, and $S(t) = S_L(t) + S_H(t)$ the total resource stock at time t.

Let $\widetilde{R}(t; S(0))$ be the overall level of extraction at time t, along an unconstrained path with total initial stock $S(0)$. Since the problem is time autonomous, we can also indicate with $\widetilde{R}(\theta, \Sigma)$ total extraction θ periods after $S = \Sigma$ is reached.

Let the *maximal Hotelling stock* for each resource be $S_i^h : \varepsilon_i \widetilde{R}(0; S_i^h) = \bar{Z}$; i.e. such that the constraint is exactly binding at $t = 0$, and never again.

Let $R_L^z(R)$ be the minimum amount of L needed to ensure $Z \leq \bar{Z}$ when total extraction equals R. Accordingly, define $S_L^z(S(t)) \equiv \int_0^{t_H} R_L^z(\tilde{R}(\theta, S(t)))\mathrm{d}\theta$, where t_H is the time it takes to reduce the stock from $S(t)$ to S_H^h along an unconstrained path, i.e. t_H solves $\tilde{R}(t_H, S(t)) = \bar{Z}/\varepsilon_H$. Thus $S_L^z(S)$ is the minimum stock of L consistent with unconstrained extraction in the economy with an announced cap, when the total initial stock is S. The corresponding maximum amount of H is then simply $S_H^z(S) = S - S_L^z(S)$. Also, let $S_L^m \equiv S_L^z(S_L^h)$, with $S_H^m(S_L^h)$ defined accordingly.

Finally, let the set of initial resource stocks for which the constraint is never binding be defined as $\mathbb{H} \equiv \{\mathbf{S_0} = \{S_L(0), S_H(0)\} : \sum_i R_i(t) = \widetilde{R}(t; S(0)) \, \forall t \cap \sum_i \varepsilon_i R_i(t') \leq \bar{Z} \, \forall t' \geqslant T\}$.

With these definitions in place we can now prove the Proposition.

Ad i. For the constraint to be binding, it must be that $Z(t) < \widetilde{Z}(t)$, over some measurable interval $\mathcal{T} = [T, T_H)$. This implies that overall extraction along the constrained path is below unconstrained extraction at least during a subset of $\mathcal{T}$. For (9) to hold, it must then be the case that over some other strictly positive time interval extraction along the constrained path exceeds $\widetilde{R}(t)$.

From (5), marginal utility grows at rate ρ during all unconstrained phases along any optimal path. Hence, if $U'(R(t))e^{-\rho t} < U'(\widetilde{R}(t))e^{-\rho t}$ for some $t \in \{(0, T), [T_H, \infty)\}$, the same holds for all t in the same interval.

Since resource extraction has to be continuous at time T_H (otherwise the Lagrangians in (2)-(3) would be discontinuous), and given that for some time after T extraction is constrained to be below the unconstrained path, it must be the case that extraction exceeds the unconstrained level during the entire $\{(0, T), [T_H, \infty)\}$ period, to satisfy the transversality conditions (9).

Ad ii. If the cap is binding at time $t \in \mathcal{T}$, $\tau(t) \geq 0$. Assume that $\lambda_H > \lambda_L$. From (4) we have that, either $\tau = 0$, and only L is used; or $\tau > 0$, implying $p_H > p_L$, which means that again only L is used. Hence, H would never used, violating (9). Thus, we must have $\lambda_H(t) \leq \lambda_L(t) \, \forall t$.

We now show that along any optimal constrained path, $\lambda_L(t) = \lambda_H(t) \, \forall t \in [0, \infty)$ if and only if $S_{L0} > S_L^m$, and $S_{H0} < \widetilde{S}_H(S_{L0}) \equiv S_H^m + \int_0^T d\left(\bar{p}_L e^{-\rho[T + (S_{L0} - S_L^m)/\bar{R}_L - t]}\right)\mathrm{d}t$.

Only if: Suppose $\lambda_L(t) = \lambda_H(t)$. Since $\mathbf{S_0} \notin \mathbb{H}$, there exists $\mathcal{T} = [T, T_H)$ such that $\tau(t) > 0$ $\forall t \in \mathcal{T}$, and $\tau(t) = 0$ elsewhere. Since $\lambda_L(t) = \lambda_H(t)$, then $R_L(t) = \bar{R}_L$ and $R_H(t) = 0$ $\forall t \in \mathcal{T}$, see (4). It follows that $S_L(T_H) \in [S_L^m, S_L^h]$, and $S_H(T_H) \in [0, S_H^m]$. Since $T_H > T$, $S_{L0} > S_L^m$.

As $S_L(T_H) \in [S_L^m, S_L^h]$, it follows that for any S_{L0}, at most $S_{L0} - S_L^m$ of L can be extracted during the constrained phase. Thus, this phase lasts at most $(S_{L0} - S_L^m)/\bar{R}_L$ periods. Since extraction must be continuous at T_H, it follows that $\lambda_H(T_H) = \lambda_L(T_H) = \bar{p}_L$. From (4) and (5), it follows that the maximum amount of H that can be extracted during the interim phase is:

$$\widetilde{\delta}_H(S_{L0}) = \int_0^T d\left(\bar{p}_L e^{-\rho[T+(S_{L0}-S_L^m)/\bar{R}_L - t]}\right) \mathrm{d}t,$$

where we have used $T_H = T + \frac{S_{L0}-S_L^m}{\bar{R}_L}$. Since $S_H(T_H) \in [0, S_H^m]$, and $R_H(t) = 0\ \forall t \in \mathcal{T}$, it follows that $S_{H0} < \widetilde{S}_H(S_{L0}) \equiv S_H^m + \widetilde{\delta}_H(S_{L0})$.

If: Suppose $\lambda_L > \lambda_H$. Assume that both S_{L0} and S_{H0} are strictly positive.

We first note that then, whenever $\tau = 0$, we cannot have simultaneous use, see (4), and that we cannot have a switch from exclusive use of one resource to exclusive use of the other resource (since it would imply a jump in price and hence in extraction, so that the Hamiltonian becomes discontinuous). Hence, $R_L = 0$ whenever $\tau = 0$, and all L must be depleted when $t \in \mathcal{T}$ to satisfy the transversality condition (9).

Second, whenever $\tau > 0$, switching from exclusive use of H to mixed use, and from mixed use to exclusive use of L cannot be optimal because (i.) exclusive use of H implies $R(t) = R_H(t) = \bar{R}_H$, while a switch to mixed use implies either lower pollution (which contradicts $\tau > 0$), or higher extraction (violating continuity), or both; (ii.) exclusive use of L implies $R(t) = R_L(t) = \bar{R}_L$, and a switch from mixed use to L-only implies either lower pollution (violating $\tau > 0$), or higher extraction (violating continuity), or both.

Third, we note that it cannot be optimal to use L immediately before the economy becomes unconstrained since any use of L at the cap implies $R(t) > \bar{R}_H$, while when $\tau(t) = 0$ only H is used, so that $R(t) \leq \bar{R}_H$ and $R(t)$ has to be continuous.

It follows that, when constrained, the economy uses both resources simultaneously until L is depleted, followed by exclusive use of H, and possibly preceded by exclusive use of L. When both fuels are used simultaneously, $Z = \bar{Z}$ and $p(t) = \lambda_H(t) + \varepsilon_H \tau(t) = \lambda_L(t) + \varepsilon_L \tau(t)$, so that $\hat{\lambda}_L = \hat{\lambda}_H = \hat{\tau} = \hat{p} = \rho$. Simultaneous use and a binding cap requires that, given a path $R(t)$ of total extraction, $R_L(t) = R_L^z(R(t))$. A price growing at rate ρ implies that $R(t)$ coincides with an unconstrained path, i.e. $R(t) = \tilde{R}(t, \Sigma)$ for some Σ. Thus, simultaneous use can at most last for the $\log(\bar{p}_L/\bar{p}_H)/\rho$ periods, during which the price grows from $\bar{p}_L$ to $\bar{p}_H$ and cumulative extraction is $\int_0^{\log(\bar{p}_L/\bar{p}_H)/\rho} R_L^z(\tilde{R}(t, S_L^h))\mathrm{d}t = S_L^m$. If $S_{L0} > S_L^m$, simultaneous use must be preceded by exclusive use of L (at $\bar{R}_L$ for $(S_{L0} - S_L^m)/\bar{R}_L$ periods) to allow full exploitation of L.

We can now calculate the minimum initial amount of H, given S_{L0}, needed to make the path derived above feasible. The minimum amount is used when the period of exclusive use of H in the constrained period is minimized, which requires τ approaching 0 at the time L is depleted, which, in turn, requires τ approaching 0 when simultaneous use starts. But then, the use of H is, by construction, equal to $\widetilde{S}_H(S_{L0})$, since this was calculated for exclusive H use between 0 and T and a zero tax after exclusive use of L.

Hence, we have proven that if $\lambda_L > \lambda_H$ and $S_{L0} > S_L^m$, we must have $S_{H0} > \widetilde{S}_H(S_{L0})$. Thus, if $\mathbf{S_0} \notin \mathbb{H}$, $S_{L0} > S_L^m$ and $S_{H0} < \widetilde{S}_H(S_{L0})$, we cannot have $\lambda_L > \lambda_H$, and we must have equal λ's.

To conclude, $S_{H0} > \widetilde{S}_H(S_{L0}) \Rightarrow \lambda_L > \lambda_H$, which entails that only H will be extracted in the interim phase. □